Chapter One

BOTANOCHEMICALS*

R. A. BUCHANAN, F. H. OTEY, AND M. O. BAGBY

Northern Regional Research Center
U.S. Department of Agriculture
Peoria, Illinois 61604

Introduction
Botanochemical Production
    Systems
    Crops
Whole-Plant Oils
Polyphenols
Hydrocarbon Polymers
Lignocellulose Conversion Products
Conclusion
References

INTRODUCTION

Energy-rich plant products useful as substitutes,
supplements or complements of petrochemicals are now
generally called botanochemicals (a term coined by the USDA
public information officer, Dean Mayberry). Botano-
chemicals include substances which can be extracted
directly from plants (primary botanochemicals) and those
made by conversion of insoluble saccharides or lignocellu-
loses (secondary or derived botanochemicals). Primary
botanochemicals include products such as naval stores (pine
chemicals), tall-oil products (paper-pulping byproducts),
oils for industrial uses, waxes, tannins, rubber, and gutta
percha. Traditional secondary botanochemicals include

* The mention of firm names or trade products does not
imply that they are endorsed or recommended by the U.S.
Department of Agriculture over other firms or similar pro-
ducts not mentioned.

1

furfural and ethanol. Potential new botanochemicals
include latex- or whole-plant oils, guayule rubber, grass
gutta, polyphenols, specialty seed oils, and such potential
lignocellulose conversion products as methane, fuel
alcohol, and various other fermentation-produced fuels and
chemical intermediates.

Now that the price of petrochemicals has increased
faster than the price of equivalent agricultural and
forestry products, the latter have become more attractive.
Various major U.S. petrochemical companies have recently
announced that they are going to make substantial invest-
ments in new technologies for producing pine chemicals,
guayule rubber, fuel alcohol from cellulosic residues,
whole-plant oils, and other botanochemicals. Thus, the
petrochemical industry appears already to have begun a
shift toward a renewable resource base. Undue delay or
failure to make this shift could eventually result in a
"Kondratiev wave" economic recession.[7]

It is especially attractive from both social and econo-
mic viewpoints to consider adaptive agricultural systems[12]
for integrated production of primary and secondary
botanochemicals, protein feeds, and fibers. Such systems
have been designated "multi-use botanochemical systems"; a
scenario was presented for their introduction into U.S.
agriculture[4] and economic and feasibility assessments were
made.[5] Such systems can potentially make farm production
of fuels and industrial feedstocks practical without
necessarily decreasing the capacity for food production.

This review surveys and discusses in a cursive way
botanochemical products from multi-use systems. Although
integrated production schemes may be applicable to special-
ty crops for oilseeds, essential oils, botanicals, plant
fibers, and vegetable dyestuffs, the discussion here rela-
tes to crops designed primarily for extraction of energy-
rich basic feedstocks, that is, oils and hydrocarbons.

BOTANOCHEMICAL PRODUCTION

Systems

Multi-use botanochemical systems offer major advantages

over other biomass utilization schemes (Figure 1). Greater
economy and higher efficiency can be achieved by codevelop-
ment of new crops and new handling, processing, and market-
ing systems than can be achieved just by making better use
of residues from conventional crops. Expensive chemical
conversion of plant products can be minimized by developing
crops specially adapted to the system and capable of
directly producing valuable energy-rich feedstocks. Leafy
residues remaining after extraction of the energy-rich
materials contain most of the plant protein and carbo-
hydrates for feeds and foods, whereas woody stem residues
are especially attractive as lignocellulose sources for
conversion to fuel alcohol. Thus, multi-use botanochemical
crop systems can make possible the agricultural production
of fuels and industrial feedstocks without necessarily
decreasing food production.

Figure 1 portrays only one optional system; crops and
processing can be varied to provide a range of primary
products. In secondary processing of woody residues, other
fermentation products can be produced besides, or in addi-
tion to, ethanol. Also, instead of saccharification
followed by fermentation, alternative processing can pro-
vide such products as solid fuel pellets, fiber and board
products, cattle feeds, furfural, process gas, methanol,
methane, or even liquid hydrocarbon fuels.

Crops. The U.S. Congress has already selected guayule
(Parthenium argentatum) for development as the crop for
domestic production of natural rubber.[20]

A screening program has so far resulted in identifica-
tion of more than 40 plant species having some potential as
new botanochemical crops.[2-4] Plant scientists and agrono-
mists are now studying genetics, reproduction, and propaga-
tion of some of these candidates to select species for crop
development. Assuming development of appropriate germplasm
and cultural protocol, specifications for practical botano-
chemical crops have been proposed.[5] Table 1 compares the
proposed crop specifications with typical compositions and
estimated yields of wild plants, but does not imply that
the new crops will necessarily be developed from the spe-
cies used for comparison.

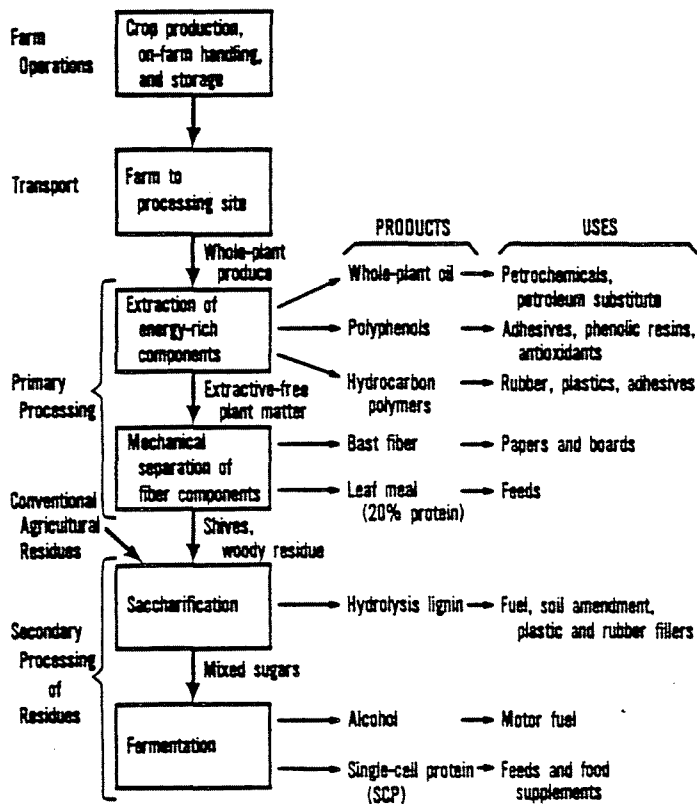In Table 1, botanochemical crops are broadly classified

Fig. 1.   Multi-use botanochemical systems.

TABLE 1
Comparison of Botanochemical Crop Specifications with Estimated Yields and Typicals Compositions of Wild Species[a]

| | Herbaceous perennial oil crop[b] | | | | Woody perennial oil-polyphenol crop[c] | | | | Perennial grass gutta crop[d] | | | |
| | Asclepias syriaca | | New crop specification | | Rhus glabra | | New crop specification | | Elymus canadensis | | New crop specification | |
Component	Composition, %	Yield, kg/ha/yr	Composition, %	Yield, kg/ha/yr	Composition, %	Yield, kg/ha/yr	Composition, %	Yield, kg/ha/yr	Composition, %	Yield, kg/ha/hr	Composition, %	Yield, kg/ha/yr
Total dry matter	100	12000	100	18000	100	8900	100	11500	100	11200	100	12500
Crude protein[e]	(11.1)	(1332)	(9)	(1620)	(6.7)	(596)	(6)	(690)	(17.2)	(1926)	(10)	(1250)
Gutta	---	---	---	---	---	---	---	---	1.9	213	12	1500
Whole-plant oil	7.6[f]	912	14[f]	2520	5.7	507	10	1150	2.8	314	8	1000
Polyphenol	7.2	864	7	1260	18.8	1673	18	2070	6.6	739	7	875
Leaf meal (20% protein)[e]	16.0	1920	32	5760	10.0	890	10	1150	---	---	---	---
Bast fiber	11.0	1320	6	1080	---	---	---	---	---	---	---	---
Residue[e]	58.2	6984	41	7830	65.5	5830	62	7130	88.7	9934	73	9125

<u>a</u> Yields and compositions are given on a dry weight basis.

<u>b</u> The new crop specification based on harvesting two crops of leafy plant per season. The Asclepias syriaca comparative data is for mature plants harvested in early September, dry yield estimated from individual plant weights and extrapolating to 107,600 plants per hectare.

<u>c</u> Woody plants handled as a coppice crop; harvested by cutting at near ground level, on a 2-year rotation. Dry yield for Rhus glabra estimated.

<u>d</u> Dry matter yields estimated on the basis of one cutting of mature plants per season. The Elymus canadensis data is from an unreplicated small cultivated plot harvested before full maturity.

<u>e</u> Crude protein is not extracted from the plant matter.

<u>f</u> This whole-plant oil contains about 20% low-molecular-weight natural rubber as a hydrocarbon component.

into three types, but actually the primary products will
differ with species. The detailed composition of whole-
plant oils and polyphenols is highly species-dependent.
However, petroleum refinery processes may be insensitive
enough to handle whole-plant oils without regard to crop
species.[8,19] Thus, crop species may be important if chemi-
cal intermediates are being produced but noncritical for
production of fuels, solvents, monomers, carbon black, and
other basic chemicals.

Whole-Plant Oils. Whole-plant oils can potentially
become major industrial feedstocks. They are like petro-
leum and the current commercial plant-derived feedstocks,
naval stores, and tall oil, in that their composition is
very complex. They are much more complex than industrial
vegetable oils consisting mainly of triglycerides from seed
or other plant storage organs. Whole-plant oils generally
contain an entire spectrum of polar to nonpolar lipids
(Figure 2). Their detailed composition depends not only on
the plant species but also on the maturity of the plant and
the method of extraction.[3]

Extraction and partitioning procedures can be varied to
produce, from a given plant sample, oils containing the
different proportions of polar and nonpolar components
desired for different applications. For example, many
temperate zone plants contain low-molecular-weight
rubber[17] that may either be isolated and used as a
polymer or be left as a hydrocarbon component of the oil.

Only a few whole-plant oils have been characterized in
detail, but lipid classes have been estimated by thin-layer
chromatography (TLC) for a defined oil-fraction from
several productive species (Table 2). A distinctive
feature of most whole-plant oils is their high content of
waxy, nonglyceride esters that are less polar than
triglycerides. Frequently, there are two distinct classes
of nonglyceride esters, probably aliphatic wax esters and
triterpenol esters (Figure 2 and Table 2).

Thus, whole-plant oils are valuable mixtures from which
a wide variety of chemical intermediates including sterols,
long-chain alcohols, rosin and fatty acids, esters, waxes,
terpenes, and other hydrocarbons could be obtained.
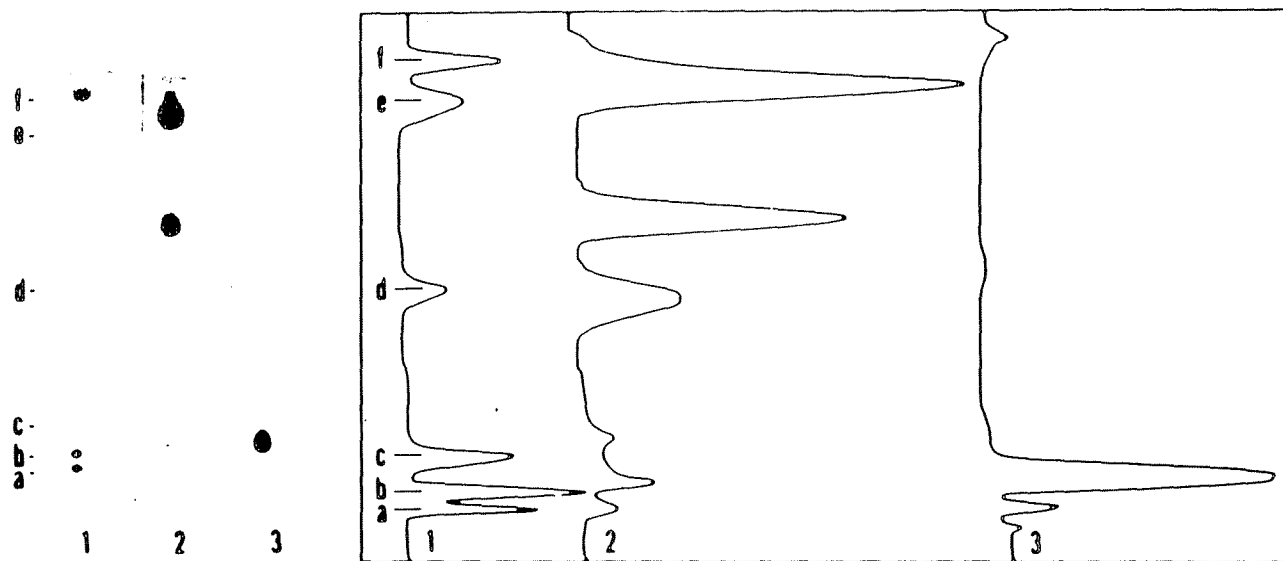However, the cost of separation is likely to be high.

Fig. 2   Thin-layer chromatography of a representative whole-plant oil. Lane 1: mixed standard
containing (a) sitosterol, R_f 0.09; (b) oleyl alcohol, R_f 0.12; (c) oleic acid, R_f 0.18;
(d) triolein, R_f 0.47; (e) oleyl laurate, R_f 0.80; and (f) squalene, R_f 0.87. Lane 2:
Cirsium discolor oil. Lane 3: Cirsium discolor unsaponifiable matter. The densitometer
traces are for the corresponding TLC Lanes with migration distance expanded 1/25 times.

TABLE 2
Lipid Classes in Whole-Plant Oils, Estimated by Thin-Layer Chromatography

Plant source	Harvest date	Oil content, %	Sterols, %	Other free alcohols, %	Free acids, %	Triglycerides, %	Nonglyceride esters, %	Hydrocarbons, %
Ambrosia trifida	9/20/77	4.21	11	4	7	68	7	3
Asclepias incarnata	7/28/77	2.70	9	15	8	13	48[a]	7
Asclepias syriaca	7/27/77	4.46	5	11	5	trace	72[a]	7
Cacalia atriplicifolia	8/3/77	2.99	10	24[b]	7	10	43	6
Campanula americana	9/8/77	6.51	13	5	10	58	10	4
Cirsium discolor	10/5/77	5.66	2	4	4	21	67[a]	2
Eupatorium altissima	9/20/77	6.08	6	5	7	36	44[a]	2
Euphorbia dentata	8/25/77	4.13	6	6	5	42	36[a]	5
Euphorbia Lathyrus	3/25/77	9.21	3	20	18	3[c]	49	7
Parthenium argentatum	5/13/77	4.04	10	7	5	23	31[a]	24
Rhus glabra	8/18/77	5.10	12	11	19	13	39	6
Sassafras albidium	9/8/77	2.26	8	46[b]	--	2	28	16
Sonchus arvensis	6/10/77	4.63	5	19	5	5	60[a]	6
Vernonia altissima	5/23/77	2.62	13	12	2	4	68[a]	1

[a] Prominent nonglyceride ester spot at RF 0.6 in addition to the one at RF 0.8.
[b] Prominent spot taken as free alcohol at RF 0.23.
[c] Small spot at RF 0.46 is unsaponifiable.

Accordingly, a likely strategy is to employ crude separations to obtain marketable fractions for various end-uses (Figure 3). Alternatively, the whole-plant oil can be used as a feedstock for a petroleum refinery by employing appropriate process modifications.[8,19] As indicated in Figure 3, whole-plant oils would be unusually versatile feedstocks for production of the entire range of petrochemicals as well as tall oil, naval store, and inedible fat products.

POLYPHENOLS

Although "polyphenols" is actually a generic term referring to a large complex of phytochemicals with hydroxy-substituted aromatic rings, we customarily use the term for crude plant extractives that are at least sparingly soluble in acetone and freely soluble in 87.5% aqueous ethanol (Figure 4). If anhydrous methanol or ethanol is used as the extraction solvent, larger yields of polyphenols of different composition are obtained as illustrated by Asclepias syriaca (Figure 5). All these crude products contain, in addition to actual polyphenols, a wide variety of complex lipids and other substances. For plants of high tannin content the polyphenol fraction might equally well be called a tannin extract (note Rhus glabra in Table 1). Acetone-extracted polyphenol fractions contain 52-60% carbon and have higher heating values than methanol but considerably lower than whole-plant oils.

Commercial tannins and bark extractives from tree species used for lumber and pulpwood have been studied with a view toward expanded industrial utilization[9,15] (Figure 6). Tannin-based plywood adhesives and water-treatment compounds are commercial products in South Africa. A polyphenol fraction from creosote bush is used as antioxidant for guayule rubber in Mexico. About 30 million kg/yr of vegetable tanning materials is imported into the U.S. However, most of the uses for polyphenols indicated in Figure 6 are only potential.

If large volumes of low-cost plant polyphenols became available, they could become very important chemical feedstocks. However, polyphenol fractions that are likely products from botanochemical processing have not been
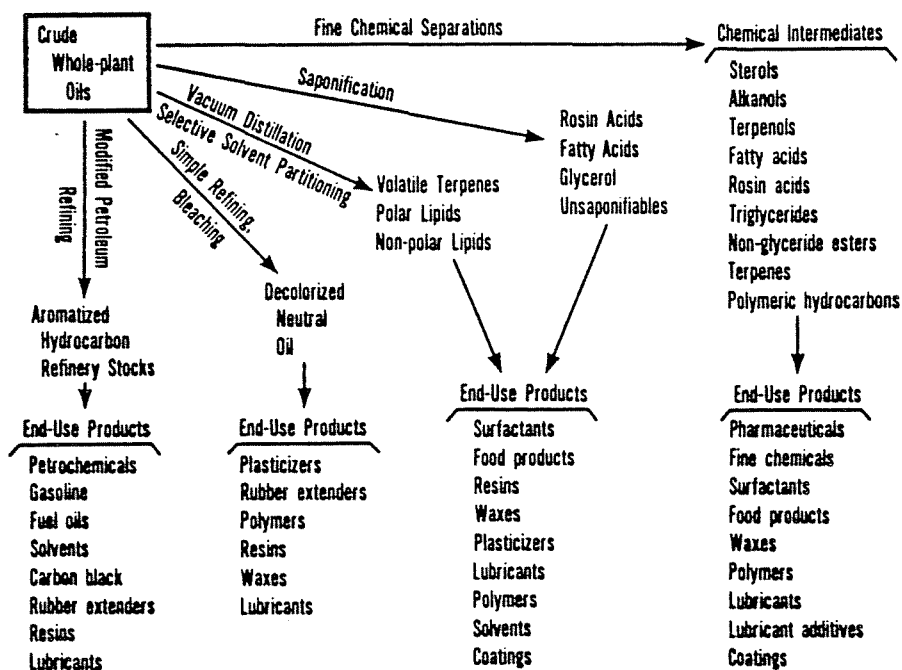
Fig. 3 Strategies for industrial utilization of whole-plant oils
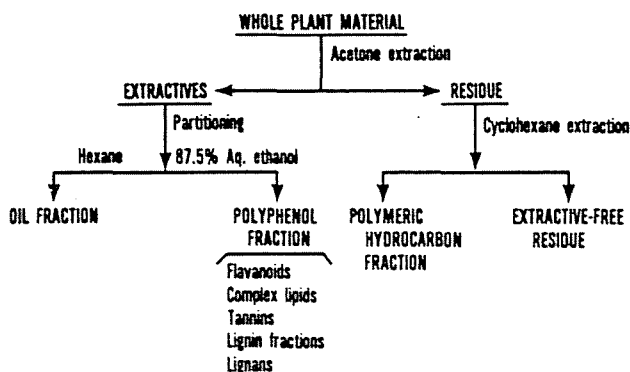

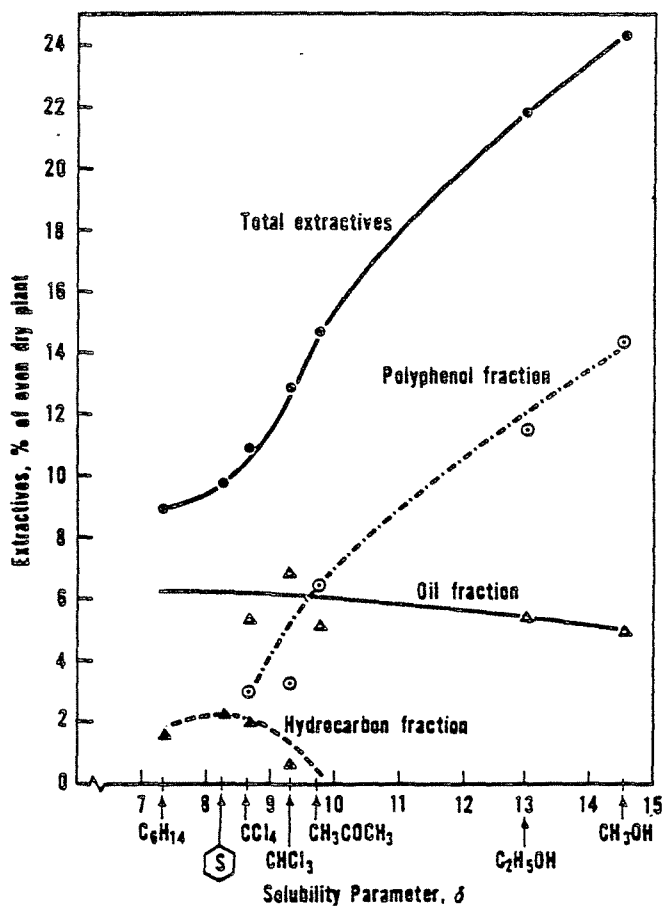Fig. 4 Separation of crude polyphenol fraction from plant materials

Fig. 5 Yield of polyphenol fraction as a function of solvent
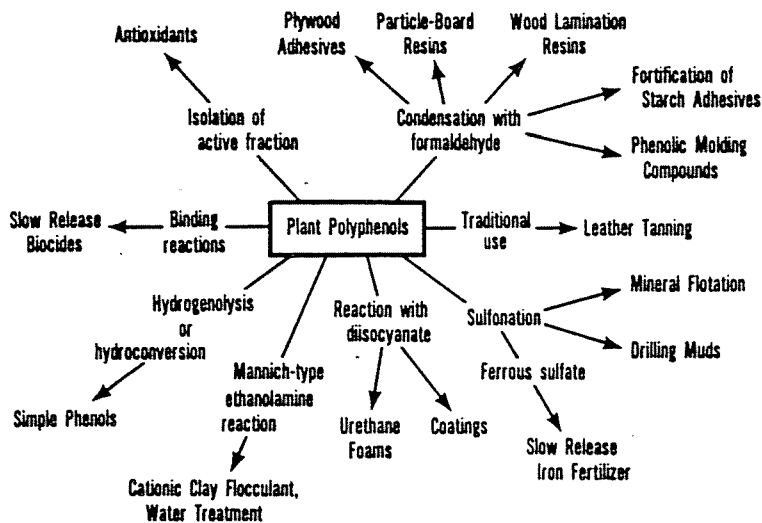   type. Exhaustive Soxhlet extraction of _Ascepias_
        syriaca.

Fig. 6 Routes to industrial utilization of crude plant polyphenols
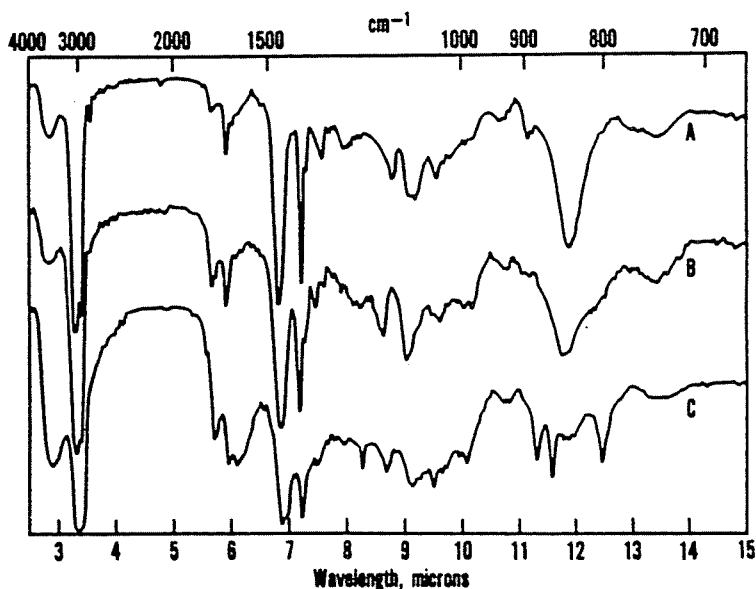
Fig. 7 Infrared spectra. A--natural rubber from Monarda .
didyma. B--amorphous gutta from Elymus canadensis.
C--crystalline gutta from Elymus canadensis

characterized. Their composition is species dependent so
that product and market development can only begin after
the new crop species have been selected. Possibly, conver-
sion to simple phenols would be less sensitive to feedstock
variations than alternative routes to utilization (Figure
6).

HYDROCARBON POLYMERS

cis-1,4-Polyisoprene (natural rubber, NR) is the most
common hydrocarbon polymer found in green plants. Since
the U.S. is now committed to producing NR for polymer uses
from guayule, other crops are less likely to be developed
specifically for high-molecular-weight rubber.

Most of the plant species identified to produce NR con-
tain less than 1%, dry whole-plant basis, of polymer that
is too low in molecular weight[17] for conventional mixing
and processing (Table 3). Low-molecular-weight natural
rubbers would be of interest as a plasticizing additive
(processing aid) to rubber mixes, for liquid rubber pro-
cessing methods, for making cements (adhesives), and if low
enough in cost as hydrocarbon feedstocks.

It would not be necessary to separate low-molecular-
weight rubber from whole-plant oils intended for use as a
petroleum refinery feedstock. Thus, perhaps the plant
breeder's goal should be to develop crop varieties high in
total content of oil plus low-molecular-weight polyiso-
prenes.

A few species of grasses may be potential sources of
gutta (trans-1,4-polyisoprene[6]) (Table 4). Known species
contain less than 2% gutta, dry whole-plant basis.
Although the molecular weights of grass guttas are lower
than those of most commercially important natural rubbers,
they are high enough for the more crystalline polymer to
have useful properties.[10] Gutta could have large-scale
applications as both a thermoplastic and a thermosetting
resin if it were available at prices competitive with NR
and synthetic polymers.

In analytical screening of plants, infrared spectro-
scopy (IR) is relied on for routine detection of isoprene

TABLE 3

Weight Average Molecular Weight ($\overline{M}_w$ and Molecular Weight Distribution (MWD) for Natural Rubbers

Genus-species	Family[a]	Common Name	M_w X 10^{-3}	MWD ($\overline{M}_w/\overline{M}_n$)
Hevea brasiliensis Mull. arg.	EUP	Rubber tree	1310	5.2
Parthenium argentatum A. Gray	COM	Guayule	1280	6.1
Pycnanthemum incanum (L.) Michx.[b]	LAB	Mountain mint	495	4.0
Lamiastrum galeobdolon (L.) Ehrend. and Polatsch.	LAB	Yellow archangel	423	4.5
Monarda fistulosa· L.	LAB	Wild bergamont	419	3.1
Vernonia fasciculata Michx.	COM	Iron weed	417	3.7
Symphoricarpos orbiculatus Moench	CAP	Coral berry	367	6.1
Sonchus arvensis L.	COM	Sow thistle	333	2.7
Xylococcus bicolor Nutt.	ERI	Two-color woodberry	333	2.8
Melissa officinalis L.	LAB	Balm	316	4.2
Lonicera tatarica L.	CAP	Tartarian honeysuckle	248	3.8
Silphium integrifolium Michx.	COM	Rosinweed	283	3.1
Helianthus hirsutus Raf.	COM	Hirsute sunflower	279	3.1
Cirsium vulgare (Savy) Ten.	COM	Bull thistle	266	3.1
Cacalia atriplicifolia L.[b]	COM	Pale Indian plantain	265	4.0
Euphorbia glyptosperma Engelm.	EUP	Ridgeseed Euphorbia	264	2.7
Monarda didyma L.	LAB	Oswego tea	263	3.2
Triosteum perfoliatum L.	CAP	Tinker's weed	240	3.8
Solidago altissima L.	COM	Tall goldenrod	239	3.0
Cirsium discolor (Muhl.) Spreng.	COM	Field thistle	238	3.1
Solidago graminifolia (L.) Salisb.	COM	Grass-leafed goldenrod	231	3.4
Apocynum cannabinum L.	APO	Indian hemp	216	2.7
Polymnia canadensis L.	COM	Leafy cup	206	3.5
Gnalphalium obtusifolium L.	COM	Fragrant cudweed	206	2.8

TABLE 3 -- continued

Genus-species	Family[a]	Common Name	M_w X 10^{-3}	MWD ($\overline{M}_w/\overline{M}_n$)
Silphium terebinthinaceum Jacq.	COM	Prairie dock	197	3.6
Euphorbia pulcherrima	EUP	Poinsettia	197	2.7
Asclepias incarnata L.	ASC	Swamp milkweed	185	2.4
Grindelia squarrosa (Pursh.) Duval	COM	Tarweed	173	2.8
Vernonia altissima Nutt.	COM	Ironweed	167	2.7
Solidago rigida L.[b]	COM	Stiff goldenrod	164	3.1
Euphorbia corollata L.	EUP	Flowering spurge	163	3.3
Helianthus grosseserratus Martens	COM	Sawtooth sunflower	160	3.8
Elaegnus multiflora Thunb.	ELA	Cherry Elaegnus	156	2.9
Rudbeckia laciniata L.	COM	Sweet coneflower	151	2.2
Pycnanthemum virginianum (L.) Durand & Jackson	LAB	Mountain mint	147	2.8
Campsis radicans (L.) Seem. exBur.	BIG	Trumpet creeper[e]	146	4.4
Chenopodium album L.	CHE	Lambsquarter	145	3.5
Monarda punctata L.	LAB	Horsemint	143	4.0
Apocynum androsaemifolium L.	APO	Spreading dogbane	140	2.9
Asclepias tuberosa L.	ASC	Butterfly weed	134	2.5
Nepeta cataria L.	LAB	Catnip	132	2.9
Teucrium canadense L.[b]	LAB	American germander	130	3.8
Solidago ohioensis Riddell	COM	Ohio goldenrod	127	2.4
Artemisia vulgaris L.	COM	Common mugwort	127	2.6
Aster laevis L.	COM	Smooth aster	125	2.3
Asclepias syriaca L.	ASC	Common milkweed	120	3.1
Artemisia abrotanum L.	COM	Southernwood	120	2.4
Campanula americana L.[b]	CAM	Tall bellflower	113	2.4
Centaurea vochinensis Bernh.	COM	Knapweed	111	2.4
Physotegia virginiana (L.) Benth.	LAB	Obedient plant	109	3.1

TABLE 3 -- continued

Genus-species	Family[a]	Common Name	$M_w \bar{X} \, 10^{-3}$	MWD $(\bar{M}_w/\bar{M}_n)$
Verbena urticifolia L.	VER	White vervain	109	2.2
Euphorbia cyparissias L.	EUP	Cypress spurge	107	1.8
Ocimum basilicum L.	LAB	Purple basil	107	3.3
Asclepias hirtella (Pennell) Woodson	ASC	Milkweed	102	2.2
Achillea millefolium L.	COM	Yarrow	98	2.3
Phyla lanceolata (Michx) Greene	VER	Frog fruit	97.2	2.2
Gaura biennis L.	ONA	Gaura	93	2.4

[a] Code, family: APO, Apocynaceae; ASC, Asclepiadaceae; BIG, Bignoniacea; CAM, Campanulaceae; CAP, Caprifoliaceae; CHE, Chenopodiaceae; COM, Compositae, ELA, Elaegnaceae; ERI, Ericaceae; EUP, Euphorbiaceae; GRA, Gramineae; LAB, Labiateae; ONA, Onagraceae; VER, Verbenaceae.

[b] Previously selected as a promising source of natural rubber on the basis of botanical characteristic and yield of rubber and hydrocarbons.

TABLE 4

Grass Gutta Polymers

Plant source	Month/day collected	Content of hydrocarbon polymer, %	Weight-average molecular weight $\bar{M}_w$ X 10^{-3})	Molecular weight distribution, $(\bar{M}_w/\bar{M}_n)$	C^{13}NMR, characterization
Agropyron repens	8/11/77	1.72	111	2.4	trans-1,4-polyisoprene
Elymus canadensis	7/28/77	1.28	116	2.4	trans-1,4-polyisoprene
Elymus canadensis	9/28/77	1.48	176	2.8	trans-1,4-polyisoprene
Elymus canadensis[a]	10/4/78	1.86	144	2.6	---
Leersia oryzoides	6/29/77	0.63	---	---	---
Leersia virginica	9/1/77	0.67	123	2.7	trans-1,4-polyisoprene
Phalaris canariensis	9/1/77	1.15	76.8	2.7	trans-1,4-polyisoprene
Phalaris canariensis	9/28/77	1.22	123	3.5	trans-1,4-polyisoprene

[a] Average values from 30 cultivated plots harvested before maturity (seeded late)..
Standard deviations in these measurements were respectively 0.40% gutta content, 16 $\bar{M}_w$, 0.4 $\bar{M}_w/\bar{M}_n$.

polymers and gutta is distinguished from rubber chiefly in
that it readily crystallizes upon standing at room
temperature[2,3,6] (Figure 7). However, this procedure would
not readily distinguish between mixed cis-trans-1,4-
polyisoprenes and the pure cis polymers. When the
polyisoprene content is high enough to merit further
characterization, nuclear magnetic resonance (NMR) is used
to determine detailed chemical structure; but so far mixed
isomers have not been identified.

The older traditional methods of detecting rubber in
plant extractives could scarcely distinguish between rubber
and gutta.[16] Thus, it is possible that there are species
producing mixed cis-trans-polyisoprenes. However, such
details of structure are immaterial from a practical view-
point for low-molecular weight polyisoprenes considered
only as a hydrocarbon source.

LIGNOCELLULOSE CONVERSION PRODUCTS

Since considerable research is in progress and several
recent symposiums and reviews have been given on biomass
conversion to fuels and feedstocks, we have limited our
discussion of this subject to the extractive-free residues
from botanochemical processing of potential new crops.
These residues would be the main product by weight of a
botanochemical extraction process and would be available as
"flakes" for subsequent chemical or microbiological conver-
sion to a wide variety of secondary botanochemical (Figure
8).

The minimum value for extractive-free residue would be
about $50/ton (July 1979) as a solid fuel. There are
several thermal-pyrolytic-catalytic routes to gaseous and
liquid fuels or petroleum substitutes from
lignocellulose.[1,11,13,14,18] Anaerobic fermentation is
another alternative route to gaseous fuel, i.e., methane.

Extractive-free residues would be especially attractive
sources of lignocellulose for saccharification to sugars
for fermentation to fuel alcohol, as suggested also in
Figure 1. Pentosans in the residue can either be converted
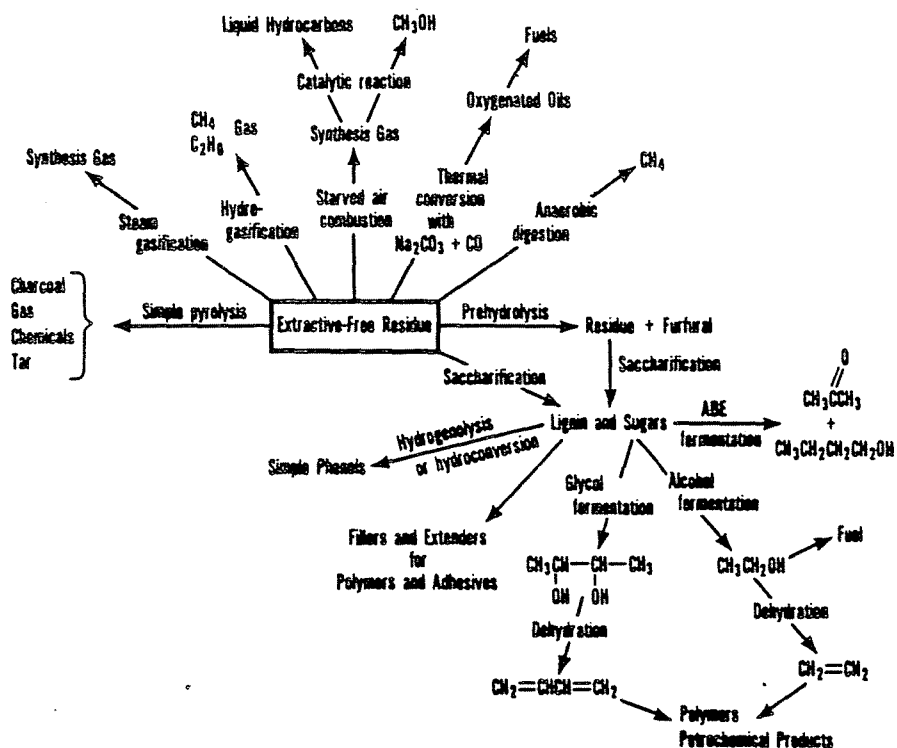to 5-carbon sugars for fermentation or to furfural.

Fig. 8   Conversion of extractive-free lignocellulosic residues
         to botanochemicals.

Other secondary botanochemicals that could be produced economically by fermentation of low-cost sugars include acetone, butanol, and 2,3-butanediol. Alternately, many of these residues could be used for nonbotanochemical applications. The process for flaking whole-plant produce can be conducted with minimum damage to the fiber so that the residue can be used for paper- or board-making. Also, any of several treatments for increasing the digestibility and the protein content of the residues would yield a valuable cattle feed.

CONCLUSION

Green plants are solar-powered chemical factories which convert CO_2 and H_2O to an immense variety of energy-rich organic compounds. As green plants grow, they efficiently store energy and materials. Crops can be developed to help meet the need for renewable sources of fuels and feedstocks, and conceptually botanochemical production systems are economically feasible. Thus, phytochemical research is now perceived as highly relevant, even urgent. Moreover, a developing opportunity exists for phytochemists to contribute to the creation of new crops, new industrial processing systems, and a new green-crop-based synthetic botanochemical industry.

REFERENCES

1. Antal, M.J., Jr. 1979. The effects of residence time, temperature and pressure on the steam gasification of biomass. Symposium, Biomass as a Nonfossil Fuel Source. 1979 Pacific Chemical Conference, Joint Meeting American Chemical Society and Chemical Society Japan, Honolulu, Hawaii, April 1-6.

2. Buchanan, R.A., I.M. Cull, F.H. Otey, and C.R. Russell. 1978a. Econ. Bot. 32:131,146.

3. Buchanan, R.A., F.H. Otey, C.R. Russell and I.M. Cull. 1978b. J. Am. Oil Chem. Soc. 55:657.

4. Buchanan, R.A. and F.H. Otey. 1979a. Multi-use oil- and
    hydrocarbon-producing crops in adaptive systems for
    food, material and energy production. In: Larrea: A
    Vast Resource of the American Deserts (E. Campos-
    Lopez and T.J. Mabry, eds.). Consejo Nacional de
    Ciencia y Technologia, D.F. Mexico.

5. Buchanan, R.A. and F.H. Otey. 1979b. Multi-use botano-
    chemical crops. Economic assessment and feasibility
    study. Symposium, Fuels and Chemical Feedstocks from
    Renewable Resources. 11th Central Regional Meeting,
    American Chemical Society, Columbus, Ohio, May 7-9.

6. Buchanan, R.A., C.L. Swanson, D. Weisleder, and I.M.
    Cull. 1979c. Phytochemistry 18:1069.

7. Gushee, D.E. 1978. Ind. Eng. Chem., Prod. Res. Dev.
    17:93.

8. Haag, W. 1979. Mobile Research and Development
    Corporation, Princeton, New Jersey, private
    communication, July.

9. Hemmingway, R.W. 1977. Bark, a renewable resource of
    specialty chemicals. Symposium, Chemicals from
    Renewable Resources. W.R. Grace and Company,
    Columbia, Maryland, November 14.

10. Kent, E.G. and F.B. Swinney. 1966. Ind. Eng. Chem.,
    Prod. Res. Dev. 5:134.

11. Kuester, J.L. 1978. Liquid fuels from biomass. AIAA/
    ASERC Conference on Solar Energy: Technology Status.
    Phoenix, Arizona, November 27-29.

12. Lipinsky, E.S. 1978. Science 199:644.

13. Molton, P.M., T.F. Demmitt, J.M. Donovan and R.K.
    Miller. 1978. Mechanism of conversion of cellulosic
    wastes to liquid fuels in alkaline solution.
    Symposium, Energy from Biomass and Wastes. Institute
    of Gas Technology, Chicago, Illinois, August 14-18.

14. Peart, R.M. 1978. Process gas from organic wastes: Corn
    cobs. Symposium, I Seminaro Sobre Energia de
    Biomasssas no Nordeste. Universidade Federal do
    Ceara, Fortalenza, Brazil, August 15-18.

15. Pizzi, A. and D.G. Roux. 1978. J. Appl. Polym. Sci. 22:
    1945.

16. Polhamus, L.G. 1967. ARS 34-74 Bulletin, Agricultural
    Research Service, USDA.

17. Swanson, C.L., R.A. Buchanan, and F.H. Otey. 1979. J.
    Appl. Polym. Sci. 23:743.

18. Waterman, W.W. and D.L. Klaas. 1976. Biomass as a long
    range source of hydrocarbons. Symposium, Shaping the
    Future of the Rubber Industry. 110th Meeting Division
    of Rubber Chemistry, ACS, San Francisco, California,
    October 5-8.

19. Weisz, P.B., W.O. Haag, and P.G. Rodewald. 1979.
    Science 206:57.

20. 95th U.S. Congress. 1978. Public Law 95-592. Native
    Latex Commercialization and Economic Development Act.